An Electro-Mobility System for Freight Service in Urban Areas

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Abstract: The paper introduces the problem of reducing impact of freight service trips in urban areas and presents the main design objectives, requirements, and steps of a new fully electric vehicle able to autonomously load and unload palletised or boxed freights. The subject is described under a multidisciplinary point of view integrating the mechatronic design, the efficient power supply system, the intelligent mobility control modules, the strategy for freight delivery planning, through a fleet of these vehicles, based on economic and behavioural modelling.

Keywords: full electric vehicle; sustainable freight service; service trips planning in urban areas intelligent mobility control.

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Evangeline Pollard obtained her signal and image processing MS in 2007 from the University of Lyons. That same year she graduated from the 'CPE-Lyons' Engineering School in electronics, telecommunications, and computing. In 2010 she obtained her PhD at the French Aerospace Lab (Onera). During 2005–2006 she worked at the German Aerospace laboratories (DLR) in Munich on the TerraSAR-X processor. After a postdoc with the Livic and the Université de Sherbrooke, Canada, for driving assistance applications, she is pursuing her work on data fusion and multi-target tracking on driving applications at Inria-Imara, Paris, France.

J.A. Dominguez started working at Mazel in 2004. He has been working developing electronic control units basically for the automotive industry, from car racing teams to standard car manufacturers. His basic competences have been in-car communication and car lighting systems. He has also specialised in wiring harness development and industrialisation for the automotive and railroad industry. Since 2010 he has been working in electromobility projects.

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1 Introduction

The freight transport has an important role in urban transport issues. Goods movement represents between 20 and 30% of vehicle kilometres corresponding to 16–50% of the emissions of air pollutants, depending on the pollutant considered, by transport activities in a city (De Jong et al., 2013). Furthermore, vehicles serving urban delivery operations are a well-established contributing factor to urban traffic congestion and increasing atmospheric pollution (Yannis et al., 2006).

The large majority of countries have not yet found adequate solutions to help optimise the urban movement of goods. It actually seems that all players are expecting initiatives to come from the other side. On the one hand, city governments expect businesses to set up new logistics services fit to the emerging needs of the customers and retailers; on the other, logistics providers wait for municipalities to initiate (and subsidise) new services before starting a business, which could prove poorly profitable and highly risky (Dablanc, 2007). A combination of commercial initiatives and government policies could be necessary in developing a sustainable urban freight system (Anderson et al., 2005). Most of the resources at the city level are focused on public transport and cars, as shown by Zunder et al. (2004) within the European project BESTUFS.

A sustainable freights transport has to fulfil the following objectives (Behrends et al., 2008):

- reduce air pollution, greenhouse gas emissions, noise to levels without negative impacts on the health of the citizens or nature
- ensure the accessibility offered by the transport system to all categories of freight transport
- improve the resource and energy efficiency and cost-effectiveness of the transportation of goods, taking into account the external costs
- contribute to the enhancement of the attractiveness and quality of the urban environment, by avoiding accidents, minimising the use of land, and without compromising the mobility of citizens.

The retail sector demonstrates how fragmentation of demand for urban freight transport (e.g., numerous independent retail outlets located in a city centre) combined with the fragmentation of supply of urban freight transport (e.g., numerous wholesalers and other suppliers using their own vehicles to make just-in-time deliveries) results in a greater number of urban freight transport movements with only part-loads than would be possible if both demand and supply were more concentrated. The larger retail chains have greater volumes of traffic and are more likely, by working with their logistics providers, to be able to optimise their deliveries in terms of overall efficiency. While diversity in the retail sector provided by small and medium-sized independent retail outlets offers greater choice for consumers and can be seen as providing wider benefits to society, economies of scale in the provision of freight transport services in all sectors tend to lead to greater logistics efficiency, lower costs, and more sustainable distribution.

Inefficiency in distribution in urban areas can be exhibited in the following ways:

- low load factors and empty running
- a high number of deliveries made to individual premises within a given time period
- long dwell times at loading and unloading points
- bad use of infrastructures (e.g., delivery areas, off-peak deliveries).

Inefficiency in distribution leads to additional costs for transport operators, which would normally be passed on to receivers/shippers (in the case of third party operators) or absorbed as costs for own account operators. These costs are ultimately borne by the wider economy. However, shippers, receivers, and their transport operators do not always have a significant incentive to increase the efficiency of the deliveries to reduce costs. This is because the transport cost is often only a small proportion of the value of the goods that are being transported and the overall costs of the shippers/receivers (MDS Transmodal Limited, 2012).

These problems related to urban freight distribution are going to increase in the future because urbanisation will bring more consumers in urban areas and more freight will be addressed to consumers since e-commerce is quickly increasing. Just some data: in Europe the total e-commerce revenue in 2012 was 305 billion of euro and 43% of the European population buys habitually online products and services (source: Eurostat) (Eurostat website, 2013). In 2012, in Italy e-commerce moved 76,000 packages each day and, comparing with 2011, the growth rate was remarkable (15%). This growth trend is expected to continue (Osservatori.net, 2013).

New solutions for urban freight distribution have been recently proposed in order to limit the number of trucks in downtown during rush hour thereby decongesting the cities, providing flexibility for recipients who recover their packages when they want to, to contribute to a better logistics organisation of malls, and decongest delivery areas. Among these new solutions, Pack stations and Bento boxes are very interesting since they reduce the capillarity of last mile freight distribution, concentrating packages in fixed point and asking the receivers to collect them.

Pack station is a service run by DHL Germany and provides automated booths for self-service collection of parcels and oversized letters as well as self-service dispatch of parcels 24 hours a day, seven days a week. The structure is fixed. The pack station can be used for both the delivery of packages to customers and by customers to send their packages. The advantage of pack station is the concentration of packages directed to customers into a few localisations; therefore no empty trips occur, as receivers have a time window to collect their packages, and the number of delivery trips is reduced thanks to the reduction of the capillarity of demand. However, pack stations register two main disadvantages:

- they have a fixed location in the urban areas and their number is fixed a priori
- the loading operations take place only at the pack stations locations.

Regarding the first disadvantage, the demand for packages varies every day in quantity and the distance between pack stations and customers may be quite high in some cases; moreover, in some cases, the available pack stations may not be sufficient to satisfy the demand or one or more pack stations may be empty. Regarding the second disadvantage, operative costs are high; moreover the road space besides the pack station may be occupied for a long time and therefore this creates some impedance to vehicular flows.

The *BentoBox*, designed within the project CityLog, with the participation of TNT Express, has been developed with the aim of resolving the second disadvantage of pack stations. It is composed of a fixed docking station and six removable modular trolleys. Trolleys are consolidated at the Urban Distribution Centre (UDC). A new small container has been proposed within the project CityLog to accommodate the trolleys: BentoBox trolleys are loaded into the small container in the UDC and unloaded at the docking station. Therefore the unloading time at the docking station is reduced to a minimum and operative costs are minimised. However, as for Pack stations, the number and the localisations of the BentoBox docking stations are fixed for a given urban area and do not depend on the current freight demand.

In this paper, new concept architectures of light duty fully electrical vehicles for efficient sustainable urban freight transport are proposed and analysed. The main paradigms of the new vehicle architecture design are energy efficiency, living city environment and eco sustainability, mobility dexterity, modularity, intelligent automated driving, and freight handling robotisation.

The architecture of the vehicle, named FURBOT, is conceived modularly: the main modules are the cab and the chassis/mobile platform. The payload is considered packaged in freights boxes or ISO pallets. The mobile platform integrates electrical modules for power generation, vehicle propulsion, and driving, together with the relative software control modules, which are explained in Muscolo et al. (2014), Dinale et al. (2013) and Molfino et al. (2014).

Freight boxes, dedicated to different kind of freights, are purposely designed together with the architecture of the FURBOT vehicle: the boxes have the same ISO pallet standard footprint size and bottom shape to be easily handled by the on-board robotised system.

In order to realise a suitable and feasible handling device for the pallets or boxes loading/unloading, the handling device was conceived both harmonised with the vehicle's chassis structure to achieve an easy integration of the overall system and, at the same time, as a separate sub-system of the vehicle, becoming hence an optional service device.

The paper is structured as follows: Section II shows the conceptual and functional design of the FURBOT vehicle, its robotic handling device, and its power supply. Section III shows the intelligent mobility control system of the vehicle. Section IV describes the service trips planning in urban areas. Finally, the possible results of the integration of these technologies and the future works are discussed.

2 FURBOT vehicle design

2.1 Requirements and vehicle layout

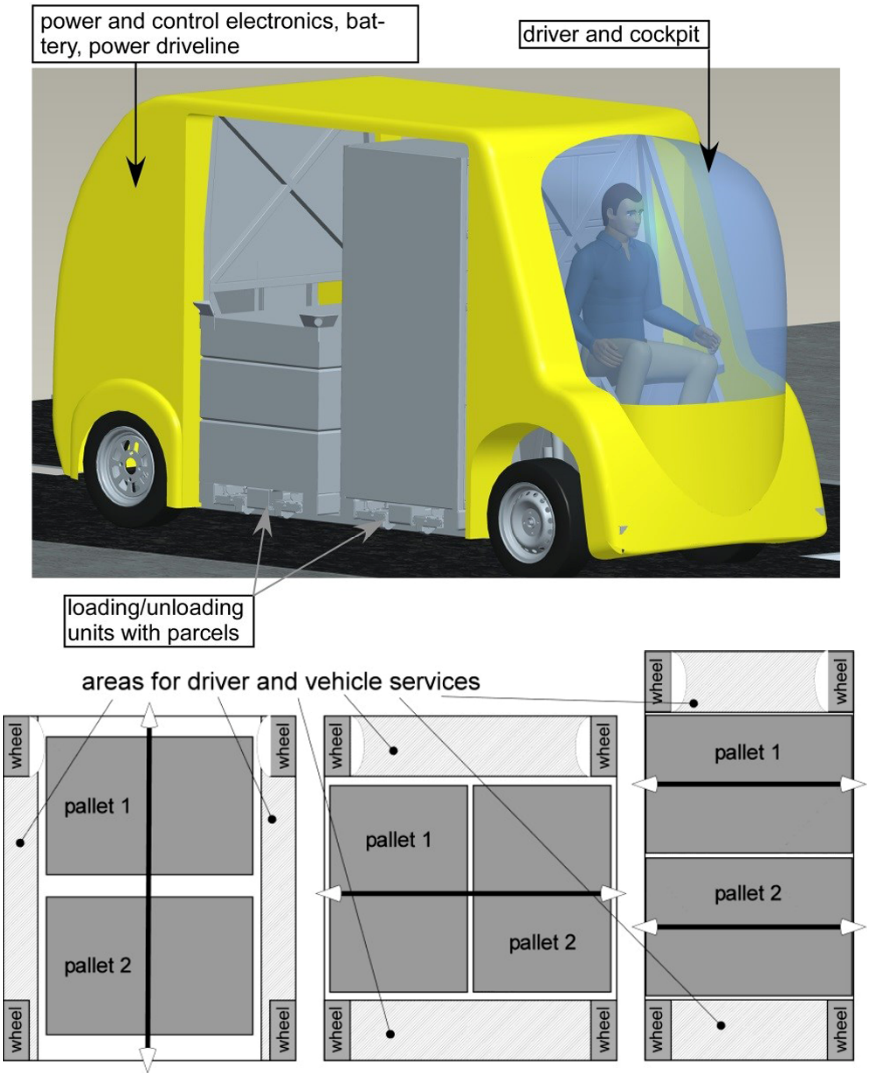
The architecture and design of the vehicle have addressed the following requirements:

- The loading/unloading process is realised from the right side of the vehicle since about 70% of the world's total road distance carries traffic on the right.
- The loading volume capacity is of two Euro-pallets (800 mm × 1200 mm) or two dedicated boxes with same base size; maximum height 1800 mm.
- The maximum total payload carried is one metric ton. The mass is distributed between the two pallets (or boxes), average 500 kg for each; an unbalance of 100 kg between the pallets is admitted (400 kg one pallet, 600 kg the other one).
- The loading of the pallets or boxes is done from the 800 mm side.

The load can be picked up directly from the ground level or from a step (typically the pavement) with a maximum height of 150 mm at a maximum distance of 500 mm from the vehicle's side.

The layout selected for the vehicle is shown in Figure 1. It has been developed to maximise the payload volume to total volume ratio, and the payload mass to total vehicle mass ratio. The choice of the layout depends on the positions of the pallets and directions of loading/unloading, and on the volume and base area required by battery, driver, wheels, motors, and control/power electronics. Simulations of vehicle manoeuvring in narrow streets (typical of pedestrian old city centres) indicate that a rectangular shape is preferable to a square shape; furthermore, the loading from sides is preferable to the loading from front/back because the parcels do not obstruct the motion of the vehicle once deposited. In conclusion, the layout adopted is with pallets in the centre loaded from sides and driver and services in the front and back of the vehicle.

Figure 1 Digital mock-up with highlight of the vehicle layout (top) and vehicle layouts studied (bottom): the layout finally selected is the one on the right (see online version for colours)



The values achieved for the objective rations on mass and volume are higher than for all existing electrical carriers: volume ratio 0.48 and mass ratio 1.05. They are also higher than for the majority of combustion engine carriers (which are advantaged by the higher energy density of fuels compared to batteries).

The main components to accommodate in the front and back are the battery, two electric motors, a driver place, cockpit and command interfaces, control and power electronics. An optimal distribution, resulting from the study of several alternative and intermediate architectures, is with battery, motors, and electronics on the back, while the front is for driver and commands. The width is the same as the pallet with an extra space for the mechanisms of the loading devices. To minimise the length, the driver is sitting with commands distributed at the sides and the door to access the cabin is in the front.

For the loading, the vehicle approaches one pallet or box at a time, parking at a side of it facing an empty slot on the loading bay. Unloading is done at reverse, with the box deposited at a side of the vehicle. The boxes are placed over a beam frame in the bottom of the loading deck. The goods, once loaded, are laid on the deck, centred with respect to the vehicle centreline plane.

2.2 The vehicle structure

The frame is made of welded AISI304 square hollow pipes. The floor of the loading bay uses four 100 mm × 40 mm × 2 mm thickness pipes with transversal connection beams (see Figure 2).

Figure 2 Prototype at shop testing (cover removed to show the inside) (see online version for colours)

The four suspensions span 180 mm vertical translation and allow to move the loading deck from driving height (maximum height) to any intermediate loading/unloading height upto deck laying on the ground (minimum height). Each suspension comprises a hydraulic ram with gas spring and a shock absorber in series; this assembly pivots on a ball joint on the chassis and is hinged to the wheel assembly. This solution is original and transforms the vehicle in a platform with height from ground adjustable continuously.

The steering of the front wheels is operated by a servo electric motor driving a mechanical commercial steering bar (Callegari et al., 2009). The traction power is 15 kW at wheels (tyre size 165/75 R14). Full loaded, the vehicle negotiates slopes up to 10% and the max speed is 30 km/h. These speed and slope capacities result from a campaign of simulations of delivery in the cities of Lisbon and Genoa with typical delivery paths.

The structural design of the frame has been developed through two sets of analyses: static for the first definition of the geometry and sections; dynamic with time variant external loads at the interfaces of the suspensions to minimise the mass of the structure.

2.3 The robotised freight handling

The loading/unloading process is automated. The vehicle is approached to the parcel by the driver. The laser scanners for the monitoring of the drive are now used to identify the relative position between vehicle and parcel; the information is used for the automatic fine self-alignment vehicle-parcel required to ensure the insertion of the forks in the slots (Muscolo et al., 2014).

Once the vehicle is fine-positioned, the following steps are applied:

- check that the distance between box/pallet is less than 500 mm and all other position tolerances are satisfied
- use the active suspensions to move the loading deck to proper height with respect to the pallet/box to load; the frame with forks translates with respect to the base and a short lift is available (120 mm), sufficient to move the bottom face of the pallet/box above the floor surface of the loading deck
- move outward the forks in lower configuration, insert them in the bottom of the pallet/box, lift up the forks, retract the forks, translate down the forks to position the pallet/box on the loading deck
- lift up the suspensions to driving height.

The unloading is done analogously in reverse order.

Frames explaining the motion of the forks during a loading cycle are shown in Figure 3. Figure 4 shows the sub-assemblies of the loading unit. Each handling unit comprises a fork translating horizontally along two telescopic rails and vertically. The fork is linked to a fork slider by four cranks forming, with the fork body, two 4-bar linkages; a vertical ram on the back actuates the translation. The fork slider translates with respect to the intermediate slider along a pair of parallel rails; actuation is provided by a ram positioned at the left side of the loading unit. The intermediate slider slides with respect to the base of the loading unit along another pair of rails parallel to the other rails; the actuation is by a ram positioned at the right side of the loading unit.

Figure 3 FURBOT unloading cycle (from top to bottom, from left to right): intermediate positions of the fork loading an empty pallet (see online version for colours)

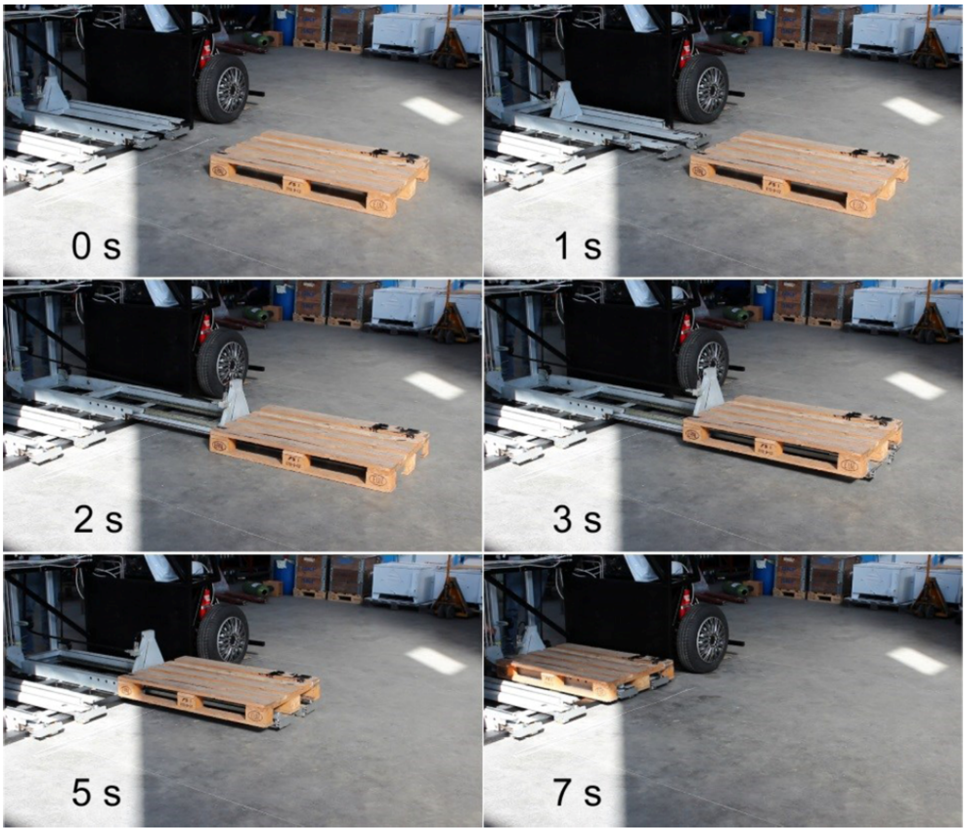
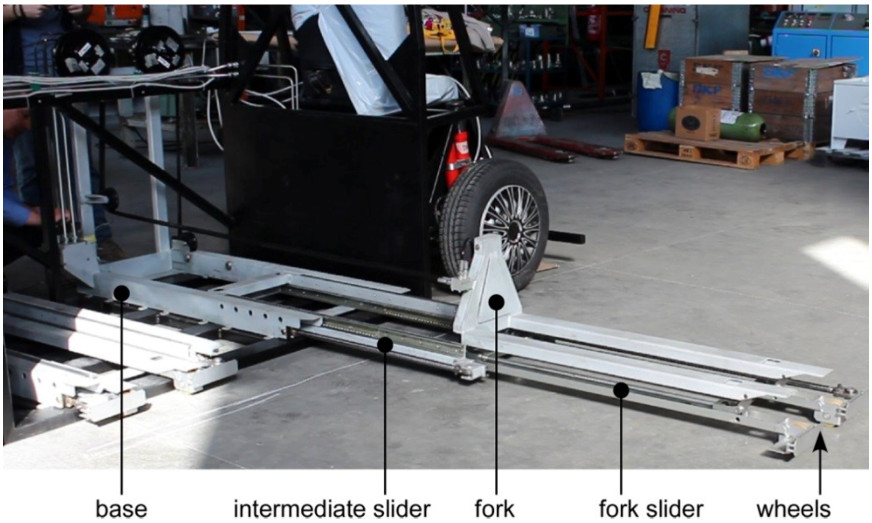


Figure 4 Subsystems of the loading unit (shown in configuration out/up) (see online version for colours)



The packaging of this assembly was especially complex due to the small section available for each fork to insert in the slot of the pallet (220 × 90 mm).

2.4 The power supply

The power supply unit is in charge of storing and providing the energy required for the operation of the vehicle. The complete system is composed of cells, the battery management system, the balancing system, the power distributor, three voltage power supplies, and the battery charger. The first step to design the power supply system was to calculate the amount of energy needed and the maximum power required. The power requirements come from the conditions of use. The main consumers are the power train, the forklift system, and the auxiliary service. The power train system is responsible for moving the vehicle and has to overcome three main forces: rolling, aerodynamic, and slope. According to calculations the force that has most influence in the power requirements is that related to the slope. As there was a restriction of 15 kW for the power train system, the power supply unit has to be able to provide this amount of power. The condition where this limit is reached is when driving on a 6% slope at 29 km/h or when driving on a 23% slope at 10 km/h. The maximum power required for the forklift systems depends on load weight and the time of operation and is around 3 kW. Finally, some estimation using standard components in the automotive and robotics industry have led to consider it around 2 kW.

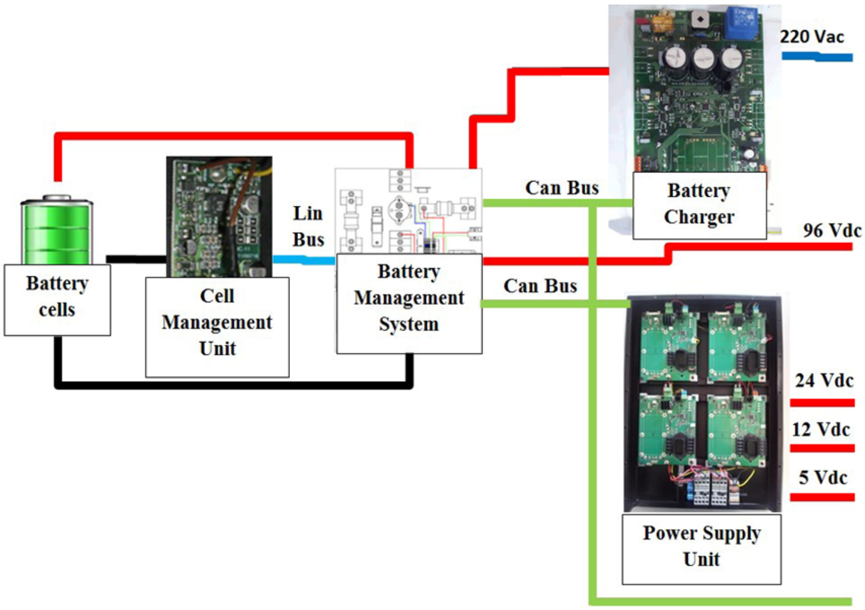
Once the maximum power is calculated, estimation about the amount of energy that has to be stored in the battery system is needed. This has to take into account the power requirements and the conditions of use. For this purpose a simple model of the vehicle was developed, taking into account only the slope and aerodynamic forces. With this model the behaviour of the vehicle in some scenarios with different terrain sections, speed, and hours of operation was simulated. With this information and the correction for the service system and forklift system, the total amount of energy has been approximated by 17 kWh.

Having the maximum power requirements and the total amount of energy needed, the next step was to decide the energy storage device. $LiFePo_4$ battery has the ability to deliver more current than its nominal current (*C* parameter). This permits to have a safety margin and be able to deliver more current to the consumers. Next step was to design the system responsible for managing the battery in order to make it work within the safety and operating limits of voltage, current, and temperature. This battery management system performs the cell balancing as well. Cell balancing is needed in order to increase battery life and to improve the overall battery system autonomy. The objective of this technique is to have all the cells with the same amount of charge and transferring charge among cells. The main features of the battery management system are SOC (state of charge) and SOH (state of health) determination, balancing management, and monitoring of critical parameters. The system transmits all this information through the CAN bus and is able to receive messages to perform some actions.

Figure 5 shows a sketch of the general architecture of the power supply.

The battery is charged with a dedicated battery charger, connected to 220 V AC and can deliver up to 5.5 A. The charger is connected to the CAN bus and receives information about the SOC of the battery and its balancing level and adjusts the amount of current with this information.

Figure 5 Sketch of the general architecture of the power supply (see online version for colours)



Another necessary feature of the power supply is that it has to be able to power all the devices in the vehicle. The main voltage of the battery is limited by the power train motors, which work at 96 V DC. Apart from these motors, there are other elements such as pumps, lights, computers, sensors, etc. that need to be powered at their nominal voltages. After a study about the electrical and electronic devices needed to perform the vehicle operation, 5 V, 12 V, and 24 V were used. The power supplies can communicate with external devices through the CAN bus and are able to detect if a fuse has been broken, the power that they are delivering, the input and output voltage, etc.

Finally, the power distribution system is in charge of managing the overall system and to determine if the battery has to be disconnected. It also contains most of the safety features such as power fuses, relays, and contactors. Apart from the traction voltage, there are separate lines with the same voltage, one dedicated to control and the other dedicated to power. The purpose of these two lines is that, in safety conditions, it is necessary that the control system will be active in order to solve the problems or to recover the system from the critical conditions. A main power contactor disconnects the overall battery system in case of safety critical operation of the battery. The driving estimated range of FURBOT operation will be around 60 km, with a total amount of 12 kWh for traction, 3 kWh for forklift system, and 2 kWh for service.

3 Intelligent mobility control system

3.1 General architecture

In addition to designing a new vehicle with a new power management system and a new forklift and an innovative freight transportation system, our goal is to create intelligent mobility illustrated in Figure 6. For this purpose, the FURBOT vehicle is equipped with many sensors (Lidar, cameras, *etc.*) in order to observe its environment and to localise itself, with computers to process these data, actuators to command the vehicle and with human machine interface (HMI) to interact with the driver. As data coming from sensors are noisy, inaccurate, and can also be unreliable or unsynchronised, the use of data fusion techniques is required in order to provide the most accurate situation assessment as possible (Hall, 1997). For this application, situation assessment consists of merging information about the vehicle state by itself (position, velocity, acceleration, battery level, *etc.*) to accurately localise the vehicle, detecting potential obstacles like other vehicles, bicycles, or pedestrians but more generally, detecting the free area where the vehicle can move also by using lane detection, and also in detecting and identifying freight boxes. To help the driver, global planning (itinerary calculation) is made using online maps. When required, local planning can be made to calculate the vehicle path and the corresponding commands for the lateral and longitudinal control are sent to the lower level. Mission orders are coming from the UDC through communication (see Section 4).

The Furbot vehicle is equipped with an embedded computer to process all these data. The general control architecture shown in Figure 6(a) has been implemented using the software RTMaps (Steux, 2000) which is a real-time prototyping system as illustrated in Figure 6(b). Each box represents an elementary process with given inputs/outputs/ properties.

Special attention has been given to the HMI. It is a web interface sharing information with real-time maps (RTMaps) through a MySql server. It will be deployed on a tablet computer, which has the advantage of being a transportable touch screen. It will play three key roles:

- provide general information to the driver on the situation assessment (itinerary, localisation, *etc.*)
- warn the driver in case of emergency
- allow the driver to choose the driving mode.

3.2 Three driving modes

In this application, the FURBOT vehicle can be driven in three different modes:

- fully manual
- assisted
- fully automated.

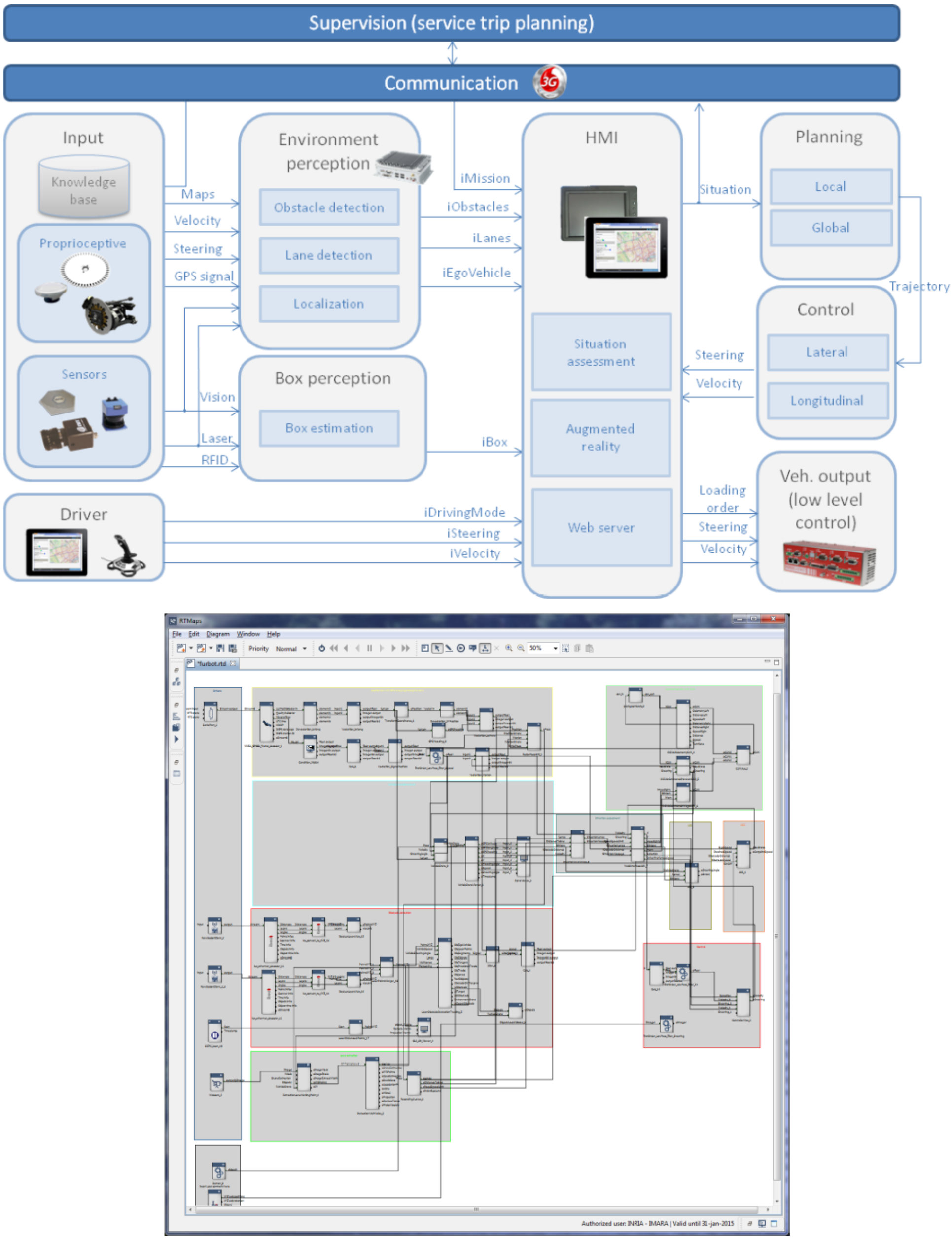
In the fully manual mode, the vehicle is driven through a joystick and the driving command is directly transmitted to the low level control. The joystick command can come from a physical joystick or from a virtual one, represented on the tablet. In this way, the driver can go down from the cabin to perform a tricky manoeuvre.

Also, in order to help the driver in the driving process, an assisted driving mode (*eg.* with advanced driver assistance systems or ADAS) is provided. The goal is to improve road safety and driver comfort. Special attention has been given to the obstacle detection and tracking for adaptive cruise control (ACC), as well as the collision risk assessment. In order to help the driver to accomplish his mission, a precise localisation is provided with a basic GPS device, proprioceptive data, and a map of the environment.

More information about algorithms are available in (Resende et al., 2013). An itinerary is proposed as part of the global planning.

The third and most ambitious driving mode is the fully automated one which is more accurately described in the next section.

Figure 6 (a) General control architecture of the Furbot vehicle and (b) its implementation with the RTMaps software (see online version for colours)



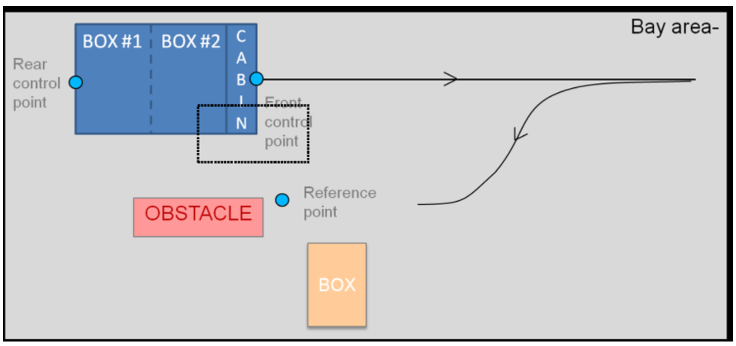
3.3 Automation of the loading/unloading stage

Several cases must be considered for the automation of box loading/unloading:

- *Loading of a box in an UDC*: In this scenario, a mission has been assigned to the driver and he is now looking for the right box to load in the UDC. He is going all over the UDC to find the box with the manual or assisted driving mode. He can then monitor the box research through the 'box' tab of the HMI. When the vehicle becomes close enough to the right box, the RFID receptor is activated by the RFID tag of the right box (from a distance of one metre) and the box is identified. The driver can visualise it in real time on the HMI through the side camera. At this moment, the automatic driving mode is available and can be chosen by the driver through the HMI. When the 'loading mode' is activated, a confirmation order message is sent and the FURBOT vehicle automatically moves until it gets well positioned regarding the box.
- *Loading of a box in bay areas*: Bay areas are located inside the cities and are chosen as flat areas with large free space to let the FURBOT vehicle go. However, contrary to the UDC, the environment is not controlled and some obstacles can obstruct the path of the FURBOT, preventing it from positioning itself regarding the box. In this case, the vehicle has to manoeuvre (front and rear manoeuvres) and elaborate complex paths to pursue its goal (see Figure 7). Bang-bang control for the time-delay system which takes into account the steering dynamics and a stable second order linear is used as made in (Perez et al., 2013).

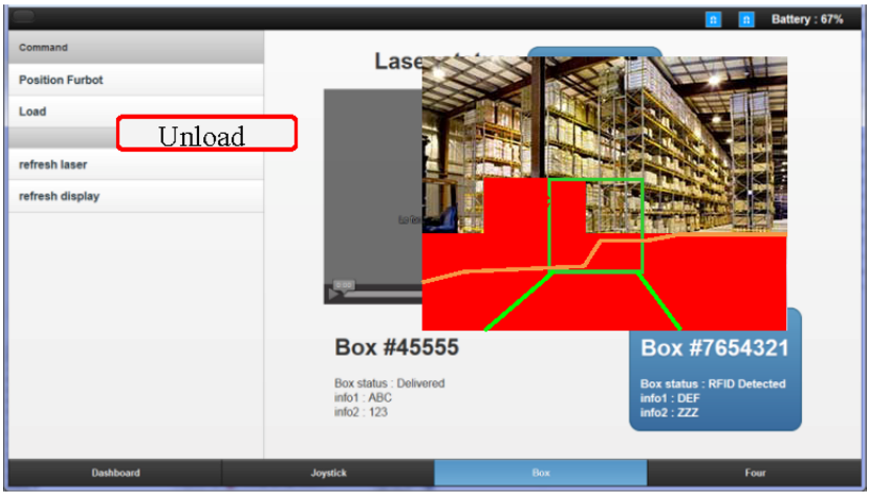
Unloading a box: For the unloading case, there is no distinction between UDC and bay areas. The driver is in charge of choosing the unloading location. The role of the system is twofold for this task. First, it has to inform the driver about the future location of the box using templates which will be projected onto the images of a video stream provided by the FURBOT external camera. It implies that the camera should point at the loading/unloading area. The second task consists in ensuring that there is enough space to unload the box. It allows the driver to choose the 'unloading mode' only if no obstacle is detected. If a moving obstacle is detected on the box path and if the collision risk increases, then the unloading process will automatically stop. Laser data are used for the obstacle detection. Laser impacts are segmented in order to detect objects and they are projected on the image to inform the driver.

Figure 7 Illustration of the box loading in a bay area with an obstacle (see online version for colours)



In Figure 8, the HMI provides some augmented reality to help the driver to choose the location of the unloading. Free space is delimited by orange colour. Bounding boxes surround the potential obstacles (here another vehicle). And the location of the box if unloaded is projected on the image. Green colour indicates that the location is free (red colour will mean the opposite), and the 'unload' button is available.

Figure 8 Augmented reality through the HMI (see online version for colours)



4 Service trips planning in urban areas

4.1 *The proposed freight transport system*

The proposed FURBOT transport system is meant to overcome the two disadvantages of pack stations described in the introduction. The number and the localisations of the FURBOT load units are not fixed a priori in the urban area and they depend on the current daily freight transport demand. The impact of the FURBOT load units on the land occupation is therefore minimum, as the load units are placed only where required. Moreover, the unloading of the FURBOT load unit is automatic.

The FURBOT system works as follows. At the beginning of the day the freight arrives at the UDC, on the border of the urban area, in pallets or in packages. Packages could be sacks, large and small boxes, envelopes and so on. Freight receivers are end consumers or retailers. Retailers and end consumers are potential FURBOT freight transport system users. While packages could be addressed to both end consumers and retailers, pallets usually are addressed only to retailers.

At the UDC, freight is split in load units. In the following, this problem is denoted as the sub-problem 1. The load units have a standard dimension: 800 mm × 1200 mm (footprint) × 1800 mm (H) maximum. There are two types of load units: the LBL box and the FBL box or pallet. A LBL box is divided in parcels (multi-parcels box) and each parcel can accommodate packages addressed to a given receiver. A FBL unit is a Euro ISO pallet or a box instead contains a Euro ISO pallet addressed to a given commercial activity place. An unloading bay is associated with each LBL box, according to the addresses of the packages contained in it. FBL boxes will be delivered at the commercial activities places. A virtual key and the actual address of the LBL box's unloading bay will be communicated to all the receivers. The receivers are then in charge of collecting their packages. A receiver has to travel from the address of his package (for instance, their home address) to the unloading bay where the LBL box containing it has been unloaded. This is an assumption of authors.

At the UDC, FURBOT vehicles are consolidated. In the following, this problem is denoted as sub-problem 2. According with the FURBOT vehicle design, each vehicle is able to carry 2 load units. Units are loaded on each vehicle, according to their unloading bays and/or commercial activity addresses. Consolidated vehicles start then the freight distribution in the urban area. According to the time at disposal for completing the freight distribution, each vehicle could perform more than one delivery trip. In a short dwell time, the units are automatically unloaded in the bays or close to commercial activity places (Muscolo et al., 2014). Text messages are sent to the receivers informing them that the freight has been delivered, indicating where it has been delivered, the PIN code to access it, and the time window available to collect the freight.

At the end of this time window, the FURBOT fleet starts to collect the load units and to carry them from the urban area to the UDC (reverse logistics). The load units could be empty or could contain freight that has not yet been collected by the receivers or packages addressed outside the urban area. In the second case, the packages will be joined to the freight that arrive at the UDC in the following day and split again in the load units.

If a freight unit is designed to only one commercial activity (FBL unit), the FURBOT system results convenient only if an unloading bay is present close to the receiver and the pallet or box is delivered by night. In this case the cost for purchasing the box is justified by the advantage of having less freight vehicles circulating during the day. If there is not any available unloading bay close to the commercial activity, the delivery can be performed only when a receiver is available for receiving the freight at the moment of delivery and no security system for the freight unit is necessary.

4.2 The system optimisation procedure

A methodology has been developed for solving the two sub-problems. The target is to minimise the daily system cost. The daily system cost *S* is the sum of the daily user cost and the daily operator cost.

The *daily system cost S* has two components: the user cost c_{user} and the operator cost c_{operator}:

$$S = \vartheta_{\text{user}} \cdot c_{\text{user}} + \vartheta_{\text{operator}} \cdot c_{\text{operator}} \tag{1}$$

where ϑ_{user} and $\vartheta_{\text{operator}}$ are weighting coefficients, assumed equal to 1.

The *daily user cost* is a function of the overall distance travelled by receivers in a day to collect their packages at the unloading bays:

$$c_{\text{user}} = c_{pd} \cdot \sum_{i=1}^{dLBL} pd_i \tag{2}$$

where

- pd_i = walking distance covered by the ith receiver: it depends on the position of the unloading bay where the package has been delivered, therefore on the number of LBL boxes (n_{LBL}) and on the box consolidation process.
- d_{LBL} = number of package receivers.
- c_{pd} = cost of an unit of walking distance, assumed to be equal for all the receivers. It has been taken equal to that for public transport users, which, according to (Shimamoto et al., 2010), is 0.36 €/min.
- The *daily operator cost* is a function of the overall distance travelled by FURBOT vehicles in a day, of the fleet dimension, and of the number of LBL and FBL load units. The daily operator cost has the following expression:

$$c_{\text{operator}} = c_{\text{LBL}} n_{\text{LBL}} + c_{\text{FBL}} n_{\text{FBL}} + c_v n_v + c_{km} q_{km} \tag{3}$$

where

- c_{LBL} = daily operative cost of a LBL box
- c_{FBL} = daily operative cost of a FBL unit
- n_{FBL} = number of FBL units: it equals the number of Euro ISO pallets and boxes that should be delivered
- n_{LBL} = number of LBL boxes the system operator decides to use
- c_v = daily cost of amortisation of a FURBOT vehicle
- n_v = number of required FURBOT vehicles: it depends on the overall travel time related to the delivery trips and the time at disposal for completing the freight distribution
- c_{km} = operative cost of running the fleet, for each km travelled by FURBOT vehicles: it is function of the vehicle power consumption and therefore of the vehicle routing
- q_{km} = the quantity of kilometres travelled by FURBOT vehicles each day.

The average fees of usage of LBL and FBL load units do not appear in this formula, as they are contemporarily user's costs and operator revenues, and therefore do not affect the daily system cost minimisation.

Every day the proposed methodology allows to assess the number of LBL boxes (n_{LBL}*), the fleet dimension n_v*, the box consolidation and the vehicle routing that minimise the system cost, given the actual freight transport demand, the road network, and the delivery time window (see Figure 9).

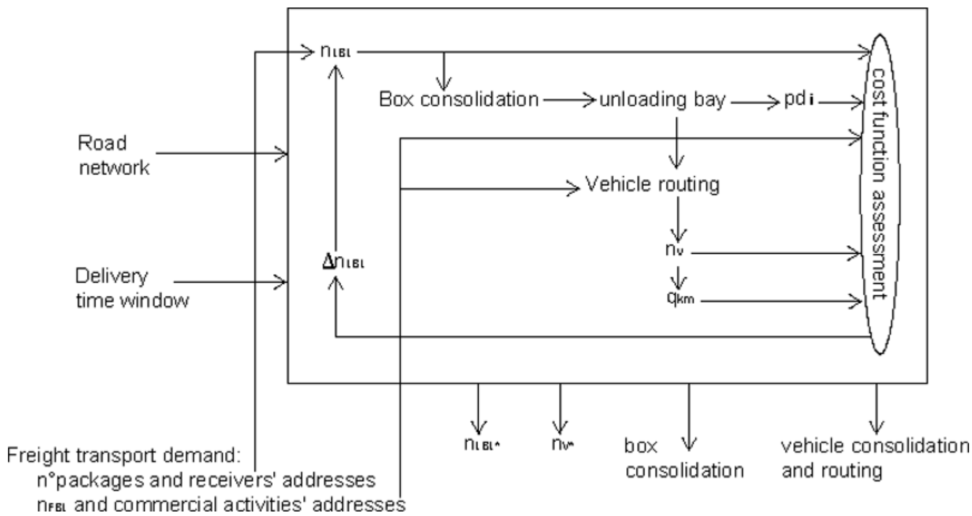
The *freight transport demand* is given in the form of a matrix, whose rows correspond to packages and pallet dimensions and columns to receiver addresses.

Regarding the road network, the authors consider the footway network, for receivers collecting their packages, and the FURBOT vehicles road network, for FURBOT vehicles performing the LBL and FBL units deliveries.

The *delivery time window* is assumed from 6 a.m. to 7:30 a.m, and from 9 a.m. to 12 a.m. It has been chosen not to perform deliveries in the morning peak period; therefore, delivery trips do not increase their duration because of road congestion, and impedance to passenger cars because of FURBOT vehicles is avoided. Moreover, during the peak hour FURBOT vehicles can be put in charge.

The proposed methodology, through a simulated annealing (SA) algorithm, explores the search space, given by the n_{LBL} admissible values, in order to minimise the daily system cost. For the case of study of the historical city centre of Genoa, Italy, the search space ranges between 1115 and 3715 *nLBL* and, with a given freight demand of 22500 packages plus 200 pallets, the methodology provided 1195 *LBL* boxes and a required fleet of 108 vehicles as optimal results. The SA algorithm converges quickly to the optimal solution. The robustness of the algorithm has been tested with different cooling schedules, neighbour search, and stopping criteria. The computation time depends on the computational time required for the box consolidation process and for the vehicle routing.

Figure 9 The optimisation methodology



The system cost, for a given n_{LBL}, is calculated by sequentially resolving *two sub-problems*, as shown in Figure 9. The *first sub-problem* optimises the *consolidation* of freight in the FURBOT LBL boxes from which the user's cost depends. Given a number *nLBL* of LBL boxes, the goal is to find the sets of packages to load in each LBL box and to define the unloading bay for each box that minimises the overall distance travelled by the receivers of the packages in the box. The problem constraints are the capacity of the box and the maximum distance that can be accepted by users. A *fuzzy k-means clustering* algorithm has been adopted. Details of this algorithm are provided in Cepolina and Farina (2013). For the case study of the historical city centre of Genoa, the optimisation of the box consolidation provides the following results: average load factor of the 1195 *LBL* boxes equal to 93%, the maximum walking distance equal to 362 metres, average walking distance equal to 24.72 metres. The robustness of the algorithm has been tested with different starting points (initial bay localisations) and stopping criteria. The computation time of the adopted methodology results very sensitive to the freight demand and slightly sensitive to the initial bay localisations.

The *second sub-problem* minimises the overall travel time related to the delivery trips from which the number of required FURBOT vehicles (n_v) depends. The travel time for each road section is assumed to be constant but it is related to the average pedestrian and vehicular flows on the road section. The FURBOT vehicle routing can be formalised as the capacitated vehicle routing problem (CVRP), with some modifications, and genetic algorithm is used to get the optimisation solution, according to (Ren, 2012). The output of the algorithm is the number of required FURBOT trips: for each FURBOT trip, the algorithm provides the identifications of the boxes that will be delivered in the trip, the travel time, the trip length, and the energy consumption. Freight deliveries take place in a given time window: therefore the required FURBOT fleet dimension could be assessed given the travel times of the required FURBOT trips and the delivery time window. Details of this algorithm are provided in Cepolina and Farina (2014). For the case study of the historical city centre of Genoa, the vehicle routing optimisation provides the following results: the required number of delivery trips is 698, the travelled kilometres are 4925.3, the maximum trip length is equal to 12 kilometres, and the average trip length is 7.0 kilometres. According to the simulation results, the power system provides enough autonomy for the longest trip, including the energy required for the forklift cycles. The robustness of the algorithm has been tested with different initial chromosomes. The routing algorithm converges quickly to the optimal solution even under a high freight demand and a wide network.

5 Conclusion

The design results addressed in the paper are in line with the Horizon 2020 objectives about measures and tools to achieve essentially zero emission city logistics in urban centres by 2030. These design results will be soon integrated in a new fully electric vehicle physical prototype endowed with an innovative and agile freight manipulation system, an efficient power supply and distribution, an intelligent multi-level online control system, and an offline policy framework, allowing sustainable urban logistics solutions through a FURBOT fleet. The achieved results have been validated through advanced virtual testing on 3D models as well as simulation of the perception motion control and the service trips planning strategies.

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